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We have carried out analyses of the CoBOP field data in order to meet the objectives regarding the use of measured IOP in the models. Results of the analysis have been published in the Limnology and Oceanography special issue (Boss and Zaneveld, 2002). This paper analyzes the distribution of IOP near the bottom and in the water column of a shallow reef and sand area at Lee Stocking, Bahamas.
We have developed a preliminary theoretical model of the near and far field reflectance of a sinusoidal bottom as it relates to the reflectance of a flat bottom with the same material (material reflectance). This model has been published in the Limnology and Oceanography special issue (Zaneveld and Boss, 2002).
We have carried out further numerical analyses of the near and far field reflectance of a sinusoidal bottom as it relates to the reflectance of a flat bottom with the same material (material reflectance).
We have further carried models that include surface wave effects, in order to determine the influence of non-flat sea surfaces and ocean bottoms on the horizontal distribution of the internal radiance. This is important as classical radiative transfer assumes that radiance distributions are plane parallel, i.e. the same at a given depth in the ocean. A paper on this topic is in preparation.

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The Influence of Bottom Morphology on Far Field Reflectance
Final Technical Report

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LONG-TERM GOALS

The long term goal of this effort is to determine the influence of the physical structure of the ocean bottom, the sea surface and the Inherent Optical Properties on radiative transfer.

OBJECTIVES

To determine the dependence of the far field optical reflectance on the following parameters:

- Material reflectance (near field reflectance)
- Bottom morphology.
- Source and detector geometries and viewing angle for passive and active sensors.

Inherent Optical Properties, sea surface, and water depth.

APPROACH

- Carry out theoretical analyses of the response of light sources and detectors of Lambertian surfaces with and without morphology. Collaborate with Dr. W. Philpot.
- We are collaborating with Drs. Carder, Wheatcroft, Voss, and Mazel in order to use realistic bottom morphologies and material reflectances measured during the CoBOP experiment.
- We include measured and modeled IOP in the numerical models.
- We make model results available to CoBOP researchers for use in closure studies. Results are prepared for publication.

WORK COMPLETED

We have carried out analyses of the CoBOP field data in order to meet the objectives regarding the use of measured IOP in the models. Results of the analysis have been published in the Limnology and Oceanography special issue (Boss and Zaneveld, 2002). This paper analyzes the distribution of IOP near the bottom and in the water column of a shallow reef and sand area at Lee Stocking, Bahamas.
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RESULTS

Measurements of inherent optical properties (IOP) were conducted over bottoms with different substrates by use of a sampling package mounted on and operated by a SCUBA diver. For a description of the sampling package and methods see Zaneveld et al., 2001. It was found that in areas of low ambient currents the distribution of IOP varies with bottom type in (1) its value relative to a nearby bottom of different type, (2) its vertical gradient, and (3) its variability. This implies that radiative transfer modeling in shallow environments may need to include, besides the bottom characteristics, the bottom effect on in-water IOP. In tidally flushed shallow banks, vertical and horizontal gradients over scales of O(1, 10 m), respectively, are as large as temporal gradients over scales of minutes and cannot be separated in our measurements. However, bottom-substrate–related processes over the banks result in gradients over large horizontal spatial scales and tidal timescales. The distribution of IOP is consistent with several biogeochemical processes that may be active at a given bottom substrate and suggest that optical measurements may provide a useful tool to infer and quantify bulk rates of biogeochemical processes. An example of a transect is shown in Fig. 1.

The results regarding variability of IOP over substrates can be summarized as follows:
1. The variability in all properties was larger over the reef.
2. Colored Dissolved Material concentration (CDM) was larger over the reef.
3. Attenuation was larger over sand, but its spectral slope was larger over the reef.
4. In most cases, the chlorophyll fluorescence was larger over sand.

In addition, we observed that the mean of a given property was, in general, higher than its median. The slope of the CDM was not significantly different between the two substrates.

The results of vertical variability of IOP can be summarized as follows:
1. The variability in all properties was larger at 10 cm above both reef and sand than further away from the bottom.
2. The CDM concentration was larger at 10 cm above the bottom than further from the bottom. The CDM spectral slope was smaller at 10 cm above both reef and sand.
3. Attenuation increased above the reef, whereas above sand, the change in concentration was not significant.

4. The attenuation spectral slope decreased with increasing distance from both sand and reef substrate.
5. Chlorophyll fluorescence increased away from substrate.

A comparison of transects above shallow seagrass beds and shallow coral reef showed no significant vertical gradients, likely due to mixing by the tidal flows.

We also examined the vertical gradients of properties within sediments. We found that during flood tide, all bottoms, varying from dense grass beds to sparse grass beds to barren carbonate sediments composed of ooids, to have higher CDM absorption than the overlying waters. During ebb tide, the barren ooids bottom was the only type to have less CDM absorption than the overlying waters. No significant differences were found in CDM spectral slope across the sediment water interface (not shown). Similar gradients were observed during January and May 2000 (e.g., Zaneveld et al. 2001).

For further details see Boss and Zaneveld, 2002.

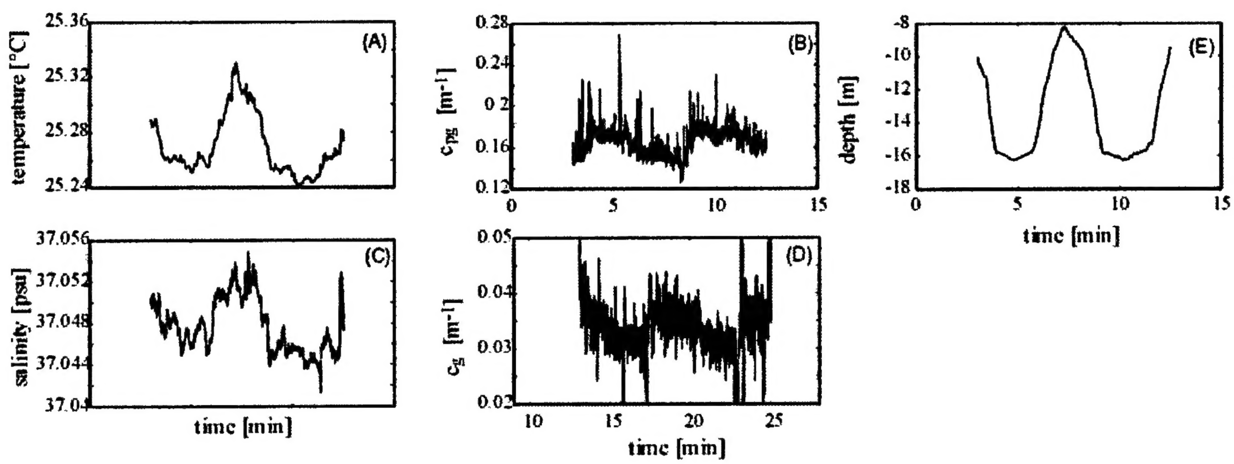

Figure 1. Transect.
[graph: Distributions of physical and optical properties obtained along a transect at a height of 10 cm above the bottom at South Perry reef (15 May 2000). The pattern sampled was a "W" string pattern laid earlier on the bottom. Properties displayed are (a) temperature, (b) attenuation at 650 nm, (c) salinity, (d) dissolved attenuation at 440 (similar to absorption), and (e) depth of diver. The dissolved measurement took place at the same location immediately after the measurement without the filter. Below 15.7 m, the bottom substrate was sand, whereas above it the substrate consisted of a mixture of coral, sponges, and macroalgae.]

The reflectance of the bottom is of importance when interpreting optical data in shallow water. Closure studies of radiative transfer, interpretation of laser line scanner data, lidar, and remote sensing in shallow waters require understanding of the bottom reflectance. In the Coastal Benthic Optical Properties experiment (CoBOP), extensive measurements of the material reflectance (reflectance very close to the bottom) were made. In carrying out closure of the radiative transfer model and observed radiometric and Inherent Optical Properties, what will be needed however is the far field reflectance.

The far field reflectance is the bottom reflectance that includes the effect of bottom morphology (such as sand ripples) as well as the material reflectance. We have derived a first order analytical model for the relationship between the material and far field reflectances. We showed that the effective reflectance of the bottom is proportional to the average cosine of the bottom slope. Using a simple 2-dimensional geometry without scattering and absorption we show that errors in ignoring the bottom morphology can lead to overestimations of the far field reflectance on the order of 30% (see Fig.1). We have thus shown that the effect of bottom morphology on the far field or effective reflectance can be substantial and cannot be ignored. We examined simple cases in which the radiance field was collimated and could be described by a single parameter, the zenith angle θ_z. Similarly we examined a simple bottom form, the saw tooth, whose slope could be described by the single angle θ_b. Depending on wavelength and amplitude this can be an approximation for both sand ripples and much larger underwater sand dunes. This resulted in the simple expression $\rho_{eff} = \rho \langle\cos|\theta_z - \theta_b|\rangle$ for the far field reflectance ρ_{eff} when the near field (flat bottom) reflectance is given by ρ.

We showed that for a flat sea surface and a saw tooth bottom with a slope around the angle of repose for loose sand, the far field reflectance can be as much as 30% smaller than the material reflectance. If there are organic materials in the bottom sediment, the angle of repose can be much larger (R. Wheatcroft, personal communication) and the far field reflectance can decrease much more. We showed that if the angle of incidence of the radiance changes away from the vertical, the far field reflectance is reduced further. In general we can thus conclude that the larger then average cosine of the light field and the larger the average slope of the bottom, the larger the deviation of the far field reflectance from the material reflectance. This would thus be a guide for where to carry out closure experiments without the influence of bottom morphology.

In the near field the reflectance depends on the horizontal and vertical placement of the sensor (see Fig. 2). This leads to the important conclusion that at least in the near field, the bottom morphology cannot be dealt with in a statistical manner. It is important whether or not the field of view of the radiance sensor primarily sees facets towards the illumination or away from it. This effect is obviously more important the larger the wavelengths of the bottom features. For further details see Zaneveld and Boss, 2002.

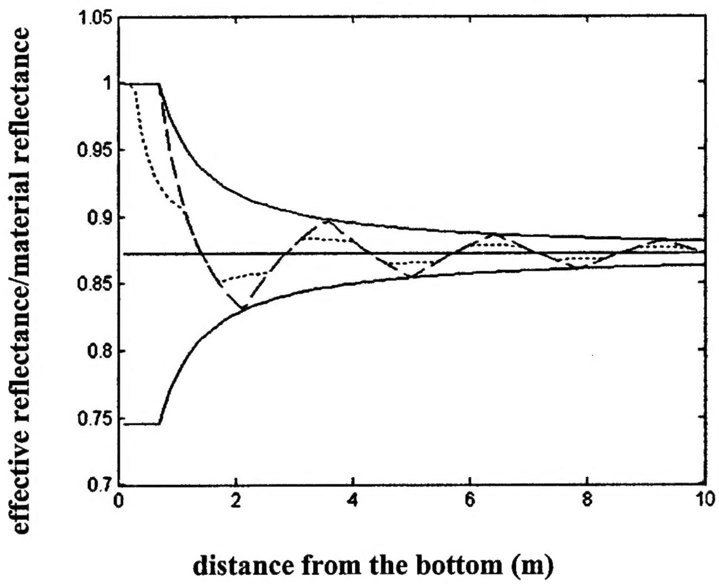

Fig.2. Example of near field effective reflection relative to the material reflection.

[graph: Near field effective reflection relative to the material reflection as a function of distance from the bottom for a saw-tooth bottom with an amplitude of 0.025 m and a wavelength of 0.25 m. The detector has a 5 degree half angle field of view. The upper and lower curves are the maximum and minimum reflectances that can be detected. The far field reflectance relative to the near material reflectance is 0.75. This is always the relative reflectance if the detector is located directly above the interface of two facets. Maximum variability is obtained when the detector is located directly above the center of a facet (dashed line). The relative reflectance is truncated when the detector is neither directly above the edge or center of a facet. The dotted line is for a detector that is directly above a point 0.2 wavelengths from the edge of a facet.]

The reflectance of the bottom is of importance when interpreting optical data in shallow water. Closure studies of radiative transfer, interpretation of laser line scanner data, lidar, and remote sensing in shallow waters require understanding of the bottom reflectance. In the Coastal Benthic Optical Properties experiment (CoBOP), extensive measurements of the material reflectance (reflectance very close to the bottom) were made. In carrying out closure of the radiative transfer model and observed radiometric and Inherent Optical Properties, what will be needed however is the far field reflectance. The far field reflectance is the bottom reflectance that includes the effect of bottom morphology (such as sand ripples) as well as the material reflectance. We have derived a first order analytical model for the relationship between the material and far field reflectances (Zaneveld and Boss, 2003). This resulted in the simple expression $\rho_{eff} = \rho <\cos|\theta_z - \theta_b|>$ for the far field reflectance, ρ_{eff},when the material (flat bottom) reflectance is given by ρ. We thus showed that the effective reflectance of the bottom is proportional to the average cosine of the bottom slope. Using a 2-dimensional geometry model without scattering and absorption we show that errors in ignoring the bottom morphology can lead to overestimations of the far field reflectance on the order of 30%. We have thus shown that the effect of bottom morphology on the far field or effective reflectance can be substantial and cannot be ignored.

We have carried out numerical simulations of the influence of various parameters on the measured upwelling radiance. Below follow examples of the effects of 1) Bottom morphology, 2) surface waves and 3) aperture of the radiance sensor on the measured radiance in the interior of the ocean. The figures show downwelling radiance by means of light rays, and upwelling radiance by means of color.

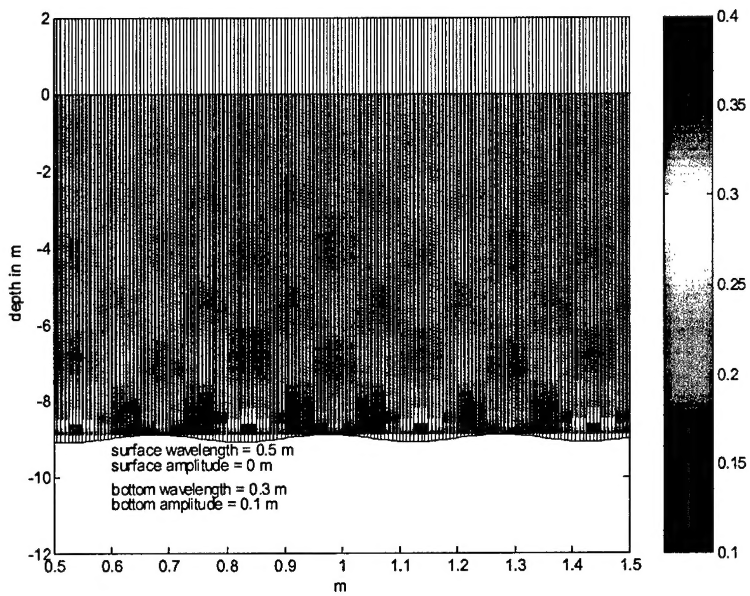

Figure 3. [The upwelling radiance distribution as shown by a color scale, above a sinusoidal bottom. The incident rays are vertical and shown by black lines. We find that the upwelling radiance has a checkerboard pattern. This is due to the finite aperture of the radiance sensor. True radiance would show vertical columns of light and dark above the light and dark bottom areas.]

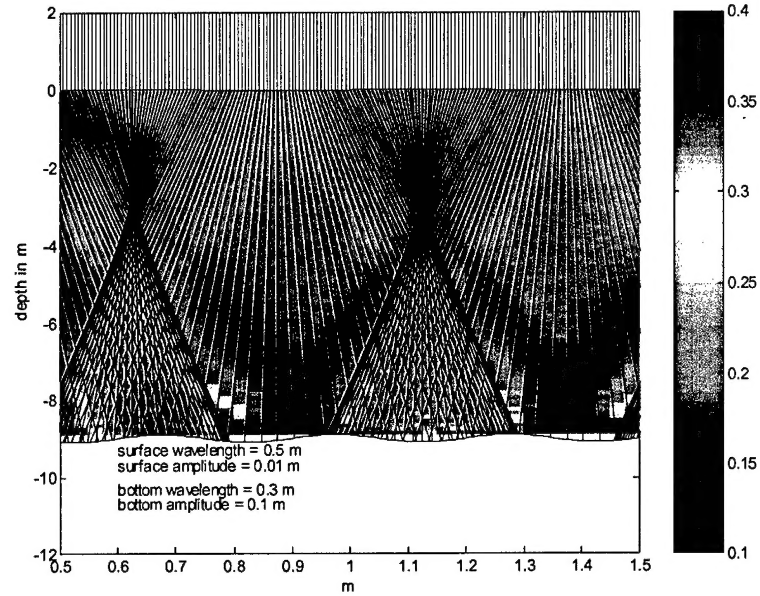

Figure 4.[Same as Figure 3, but with a very small amplitude surface wave added. The checkerboard pattern of upwelling radiance is overwhelmed by wave refraction patterns reflected off the bottom. The refraction pattern is indicated by the black lines, representing rays. Downwelling irradiance is proportional to the horizontal number density of the rays.]

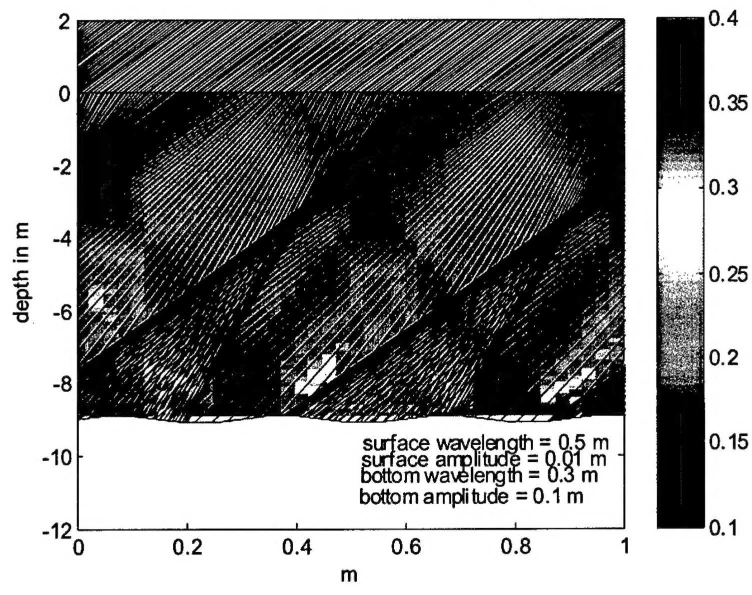

Figure 5. [Same as Figure 4, but with a changed angle of incidence. This does not affect the upwelling radiance distribution very much. The bright spots on the bottom are still due to the rays refracted by the surface wave. The upwelled radiance distribution in the interior is primarily due to the downwelling irradiance distribution on the bottom.]

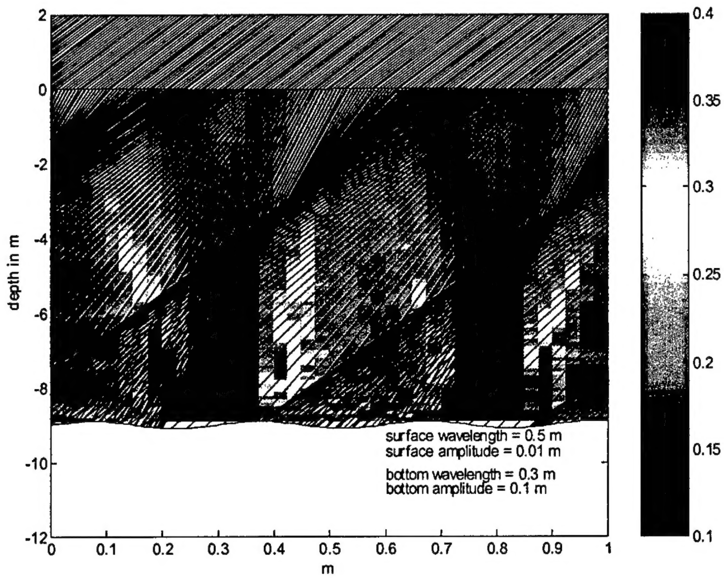

Figure 6.[Same as figure 5, but with the aperture of the radiance sensor decreased from a 3° to a 1° half angle. This changes the measured radiance distribution in the interior. In the limit of 0 °, the radiance maxima are directly above the bright spots. The measurement of radiance is thus significantly influenced by instrument parameters.]

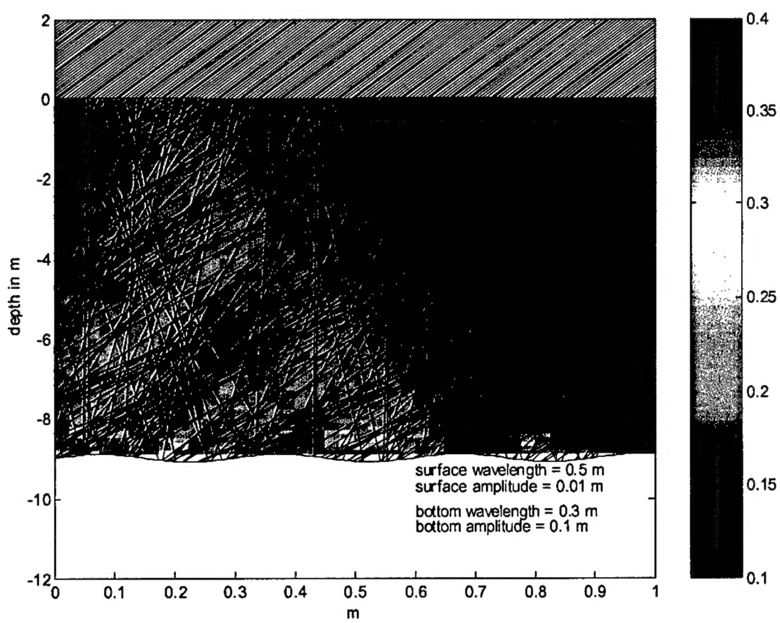

Figure 7. [The same as Figure 6, but with a very small capillary wave (wavelength of 2cm and amplitude of 1mm) added to the sea surface. This scrambles the light rays. There are still bright spots on the bottom, generating increased upwelled radiance locally.]

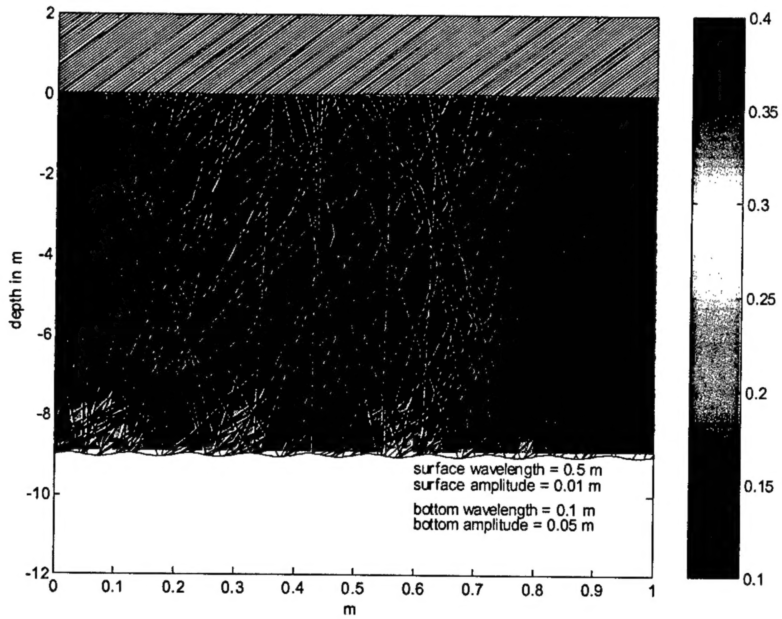

Figure 8. [The same sea surface as Figure 7. but with a different bottom. It is shown that increasing the average slope of the bottom features decreases the upwelling radiance(as shown by the color scale) in the interior, as predicted by the theory that says that the far field reflectance is proportional to the average slope of the bottom.]

IMPACT/APPLICATIONS

We have provided a method for the measurement of small scale horizontal variability of optical and physical parameters in the benthic environment. We have shown that the gradients in IOP reflect the metabolic processes associated with a coral reef. A major application of this data is to test the plane parallel assumption often used in radiative transfer i.e. it is assumed that IOP do not vary horizontally. Our measurements show that the IOP above coral reefs are not homogeneous horizontally or vertically We have pioneered a new method of measuring pore-water CDOM absorption and physical properties in-situ.

We have shown theoretically that the far field reflectance is equal to the average cosine of the bottom morphology. We have derived a model for the near-field reflectance as a function of the bottom morphology and the material (flat bottom) reflectance.

Our work will have a significant impact on the interpretation of measured radiance distributions in shallow water, with surface waves and bottom features. Future experimental and theoretical work must take the following into account:
1) For parallel rays the reflectance of a bottom can be simply described as the material reflectance multiplied by the average cosine of the angle of the bottom relative to the incoming rays.

2) For a given bottom morphology the near field reflectance depends on the orientation of the bottom features relative to the light source and the detector. This leads to a complex upwelling radiance distribution.
3) Surface waves scramble the direction of the rays near the bottom so that the upwelling radiance distribution in the interior is dominated by the refraction of the rays at the surface and their reflection off the bottom.
4) Measured radiance distributions depend on the aperture of the radiance detector.

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